Communications with Curiosity during Solar Conjunction

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Abstract— This study examines the methodology for operating and communicating with NASA's Curiosity Rover (MSL) during the 2019 solar conjunction. For MSL, solar conjunction occurs when the viewing angle between the Sun and Mars from Earth's perspective falls below 3 degrees, which occurs roughly every two Earth years and lasts for about two weeks. This presents a challenge for engineers operating a vehicle on Mars because the degraded signal to noise ratio disrupts data flow between Earth and the spacecraft. As a result, operators designate a command moratorium in which no commands are sent to the rover and instead design long-term plans that are uplinked weeks in advance (rather than the nominal case of daily uplinks). Coordinating communications with the rover leading up to and following conjunction requires negotiations with several orbiters, another lander, and the Deep Space Network (DSN) – each with their own set of constraints. It is the Strategic Comm Planning Team's job to oversee this coordination, which acts as a baseline for the conjunction planning cadence. In the 2019 conjunction, MSL's Comm team faced additional complications such as the arrival of two new spacecraft at Mars – NASA's InSight (NSY) and the ESA-Roscosmos ExoMars Trace Gas Orbiter (TGO). The team also utilized a set of new, complex planning tools that were developed to handle the intricate incorporation of these new spacecraft into the Mars relay environment, but which had never before been used for conjunction communication planning. Although experience with previous conjunctions provides guidance, each conjunction period presents unique challenges and finding the optimal solution each time is one of the hardest challenges that the Comm team faces.

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1. INTRODUCTION

Mars Science Laboratory

Mars Science Laboratory (MSL) is a NASA Jet Propulsion Lab (JPL) built and operated asset that landed in Gale Crater on Mars in August 2012. Its primary mission was – and still is – to determine if Mars was ever home to microbial life and to explore its surface to learn more about the planet's history. MSL is equipped with a suite of 10 instruments, a robotic arm, and a vast array of cameras to gather data about its environment. Upon landing, MSL was quickly able to find evidence that vast amounts of liquid water once existed on Mars's surface, and it continues to rove the Martian landscape conducting experiments on local geology.

Operations and Relay

MSL receives daily sets of instructions from operations engineers at JPL and scientists around the world. These instructions consist of a complex set of commands that the rover executes in sequence usually over the span of one to three Martian days (called sols). This planning cadence is determined based on whether or not operators have received data back from the rover to help inform their next decisions, e.g. imaging of a specific science target or information about the success or failure of a planned activity. This timely data is referred to as "decisional" data, and is a key aspect of rover operations. The past and current generations of landers require human-in-the-loop reliance on decisional data because they lack fully autonomous capabilities. Future generations of rovers intend to reduce the need for human-in-the-loop planning.

Data that MSL collects each day is sent back to Earth via relay, first sending data via its Ultra High Frequency (UHF) radio to an orbiter, which then relays data to one of the large arrays of antennas on Earth called the Deep Space Network (DSN). This provides a considerably more efficient and reliable means of returning data than communicating directly to Earth from MSL's High Gain Antenna (HGA), which yields significantly slower transmission rates than its UHF radio. MSL uses 4 orbiters for relay – Mars Odyssey (ODY), Mars Reconnaissance Orbiter (MRO), Mars Atmosphere and Volatile EvolutioN (MVN), and ExoMars Trace Gas Orbiter (TGO). It also exercises the capability to conduct relay with Mars Express (MEX), but does not utilize the capability in nominal operations.

Relay Planning Process

Relay planning is an iterative process in which MSL's Strategic Communications Planning Team (Comm planning) identifies potential windows for the rover and orbiters to communicate, called orbiter "overflights" or "passes." These windows are identified and categorized based on the geometry and timing of their orbits. Overflights with "good" geometry typically consist of long view periods between the orbiter and the rover and have high elevation relative to the horizon, allowing plenty of time for the rover and orbiter signals to lock onto each other and communicate. This typically yields high data volume. There are many additional considerations for categorizing overflights such as timing and latency (the delay between sending data to the orbiter and receiving data on the ground) that will not be discussed in detail in this study, but have been discussed in other papers. [1, 2].

The arrival of the NASA lander InSight (NSY) marked the start of a new era for Comm planning on Mars. While MSL operated for over 5 years with the Mars Exploration Rover (MER B Opportunity) also operating on the surface, the two missions were never required to coordinate their relay communications between themselves and orbiters because they were located on opposite sides of the planet. Thus, there were no individual overflights occurring at exactly the same time for both rovers. NSY, however, landed roughly 600 km from MSL, meaning that both surface assets have concurrent view periods of orbiters in the sky. This means that MSL and NSY must negotiate the use of orbiters as relay assets to prevent "crosstalk," which is the interference between concurrent, collocated telecommunications. Negotiations are now a routine part of the communications planning process, and though initial implementation complicated the standard process, a new set of predetermined agreements and suite of dedicated tools now help facilitate MSL and NSY's negotiations.

In brief, the standard process for overflight selection consists of the following: the Comm planning team determines candidate overflights for a 2-week period called a *planning period* (or *cycle*) based on multiple input files that contain ephemeris and availability information for each orbiter. MSL submits a *Tentative* request to use the candidate overflight for relay. The NSY Comm planning team reviews MSL's Tentatives and the teams negotiate to resolve any potential conflicts. The Tentatives then become *Proposals*, which later become official *Requests* once more refined input files reflecting more certain overflight parameters become available. Requests are the final stage of selection before an overflight is implemented and sequenced by both orbiter and lander teams. Figure A portrays this process. There are several steps in the process that must be performed serially and cannot be parallelized.

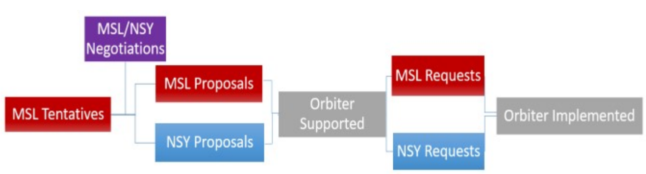

Figure A: Relay Planning Block Diagram

Orbiter Sequencing

Martian orbiters tend to operate using command sequences which span several weeks, coinciding with their planning period. This contrasts surface spacecraft's near-daily operations. Orbiters incorporate MSL and NSY's relay requests into their sequences and designate specific time for relay and specific time for gathering science data. Orbiter teams receive periodic downlinks every several hours based on need and DSN availability. These downlinks include both the rover relay data and orbiter science data.

2. BACKGROUND

Conjunction

Solar conjunction is a phenomenon that arises from the geometry of two bodies orbiting the sun; when the Sun eclipses the line of sight between the two, telecommunications become disrupted [Figure B]. The effects are most significant at smaller separation angles between the Sun and Mars (SEM angle). Figure C illustrates SEM vs. date for the 2019 conjunction. SEM reached 1.08 degrees on Sept 2, 2019.

The Sun's radiation dramatically degrades the integrity of the signal between the DSN and spacecraft in orbit and on the surface of Mars. Figure D demonstrates the difference in DSN measured Doppler noise from MRO as conjunction approaches. This serves as a good analogue to demonstrate signal integrity as a function of angle of separation between the Sun and Mars (SEM). As SEM decreases, measures of signal interruption like Doppler noise and Signal to Noise ratio increase.

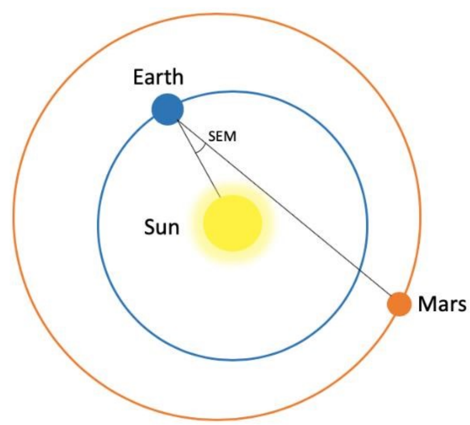

Figure B: Sun-Earth-Mars Conjunction Geometry

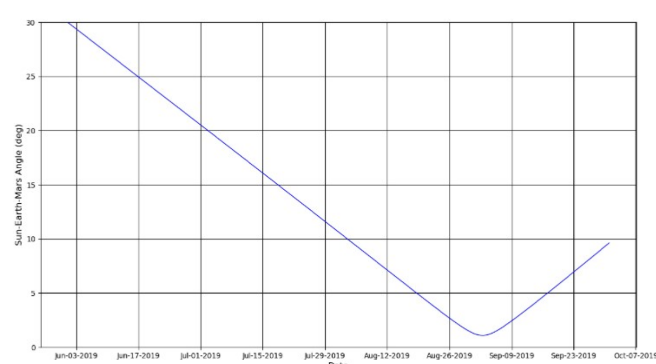

Figure C: 2019 SEM Angle Plot. The minimum Sun-Earth-Mars angle is 1.08 deg on September 2, 2019

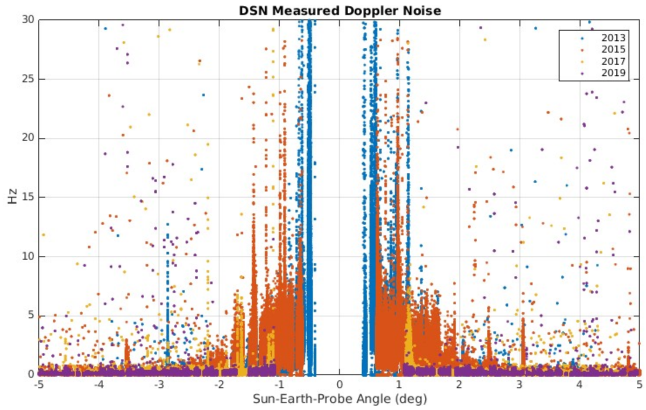

Figure D: MRO Doppler Noise (Hz) vs. SEP angle (deg) approaching conjunction [Christopher Leeds, 2019]

With all communication to the rover halted, the problem for MSL during conjunction is ensuring that the vehicle has activities to (safely) execute during the two week period in which the operators cannot directly communicate with it. The alternative is to let the rover sit idle for the duration of conjunction thus wasting valuable time that could be spent collecting science. Orbiter teams, which are accustomed to sequencing over spans of multiple weeks, do not face the same problem. The solution for MSL is to uplink significantly longer-than-usual "conjunction plans" to ensure the rover makes use of this time. These plans are heavily constrained by a variety of factors and are thus sparser than nominal plans – but nonetheless, they yield valuable science.

In previous conjunctions, anomalies have occurred which resulted in a loss of science. Most notably, during the 2017 conjunction, MER experienced an anomaly which caused an onboard response prohibiting the set of conjunction plans from executing. Although root cause was never conclusively determined, the leading theory is that a solar event disrupted telecommunication and caused the rover's high gain antenna to lose positional knowledge. The result for the mission was nearly two weeks of unutilized time. This case demonstrates the potential risk posed by the lack of communication with the spacecraft. In another scenario, two weeks without communication could pose an even greater health and safety risk. Conjunction plans span approximately 2 weeks, making them the longest set of activities that are ever sent to the rover, so it is important that the plans themselves do not include any high-risk activities.

3. NEGOTIATIONS

The 2019 conjunction was unique to all previous conjunctions in a variety of ways. Foremost, NSY arrived at Mars in 2018 and two orbiters, MVN and TGO, would participate as relay orbiters for MSL during conjunction for the first time. As mentioned, MSL's Comm planning process changed significantly with the arrival of NSY, and incorporating MVN and TGO into negotiations added even more complexity. The number of parties involved meant that the 2019 conjunction would be the most complicated conjunction in terms of negotiations thus far. With four orbiters and two landers each trying to ensure their spacecraft's safety while maximizing their science return, the process required an iterative approach. In addition, each had their own timeline and constraints, which had to be considered when planning the MSL timeline.

The Mars community began discussing the conjunction plans in March during a bi-weekly recurring meeting. These discussions also included the relay plans for the weeks going into and coming out of conjunction. Aside from TGO and NSY, the other Mars projects had solar conjunction experience to draw on having gone through conjunction before, so they followed strategies similar to previous years while applying lessons learned from the last solar conjunction in 2017.

Schedule

A schedule was needed to coordinate the delivery of the numerous input and output files between teams. MSL's process of establishing a schedule was one of working backwards. The MSL team needed to make roughly two weeks of conjunction plans corresponding with a designated SEM of 3 degrees inbound to 2.5 degrees outbound (Aug 25 – SEM 10). The team factored in two days of emergency planning time in case the initial uplink of the conjunction plans was unsuccessful, making the nominal uplink date August 23. From there, MSL determined dates that all inputs from the orbiters would be required, and negotiated with other missions to establish a baseline off which teams could iterate. Some due dates were further in advance than in standard operations. In general, creating accurate input files further in advance is difficult for orbiters because there is inherent uncertainty in orbital geometry that grows with time. For this conjunction, the timing uncertainty was low enough that MSL only needed to add minimal margin to overflight timing calculations to account for uncertainty.

The schedule continued to be negotiated and refined over several months. The Mars Program Office held a review in May 2019 where the orbiters and landers presented their amended conjunction plans and discussed constraints, health and safety information, and finer details regarding their telecommunication plans. After May, the schedule had been refined, but there were still a few lingering items that inherently could not be finalized until a later date. Discussions continued until August. One of the largest takeaways that was apparent after this review and from continuing negotiations was that one delivery deadline would be an entire two weeks early. Knowing this well in advance helped all teams prepare for the unusually early cycle.

The final calendar resulting from all negotiations is shown in Figure E.

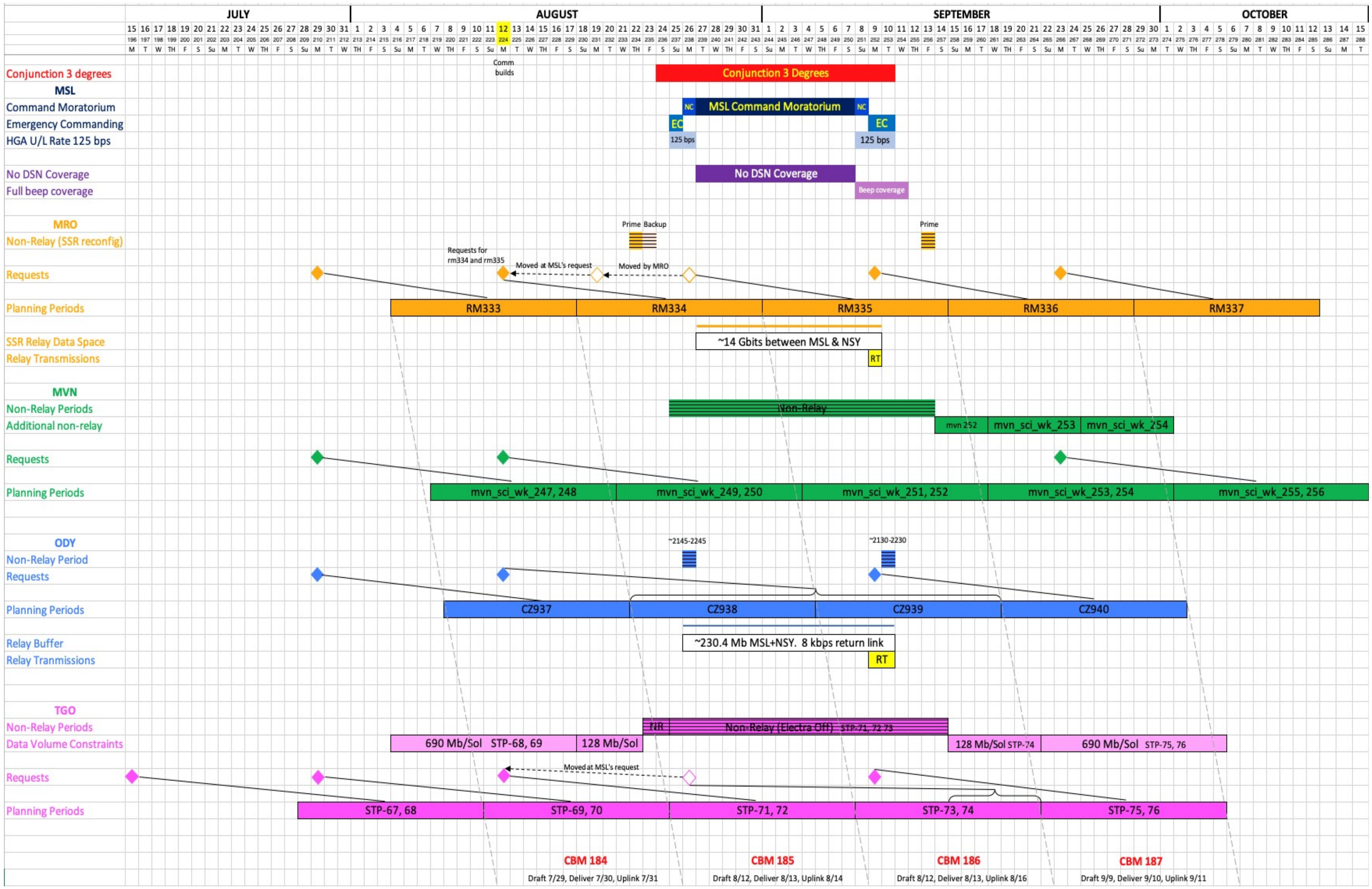

Figure E: Conjunction schedule summary for MSL and all orbiters

4. AGREEMENTS

After negotiations, it was determined that MSL would receive relay coverage during conjunction from only ODY and MRO. Although MSL's science requirements were not finalized by the time this agreement was reached, this coverage would prove to be sufficient. ODY would attempt to continue relay throughout conjunction, as it had in previous conjunctions, while MRO would not. TGO and MVN would not perform relay during conjunction, but would have pre- and post-conjunction requirements that MSL had to comply with. MSL would refrain from deleting any data onboard the rover until the end of conjunction in case data was lost in relay during that period.

ODY

Out of all the Mars missions involved in the 2019 conjunction, ODY had the most conjunction experience with 2019 being their ninth solar conjunction. ODY followed previous conjunction strategies but tweaked them based on lessons learned from 2017. ODY would once again be the sole orbiter to attempt to continue relay throughout conjunction. Analysis from previous conjunctions suggested that the relay data should return relatively intact, with more corruption at smaller SEM angles.

In addition to transmitting data back to Earth during conjunction, ODY stored all data onboard until it could relay all of the data at once at conjunction's end. If the first transmission was successful, this would be duplicate data. This approach required ODY to reformat its memory buffers to allocate a specific portion of memory to relay data. Typically, 286 Mb of ODY's memory is allocated for relay data while the rest is allocated for science and engineering data. During conjunction, the ODY relay buffer allocation for both MSL and NSY during the conjunction period was 230 Mbit for the entire period, which was split evenly between the two landers. MSL routinely sends many times this amount of data volume in a single MVN or TGO overflight, so adhering to this number was a challenge. This number was suggested because ODY has a ring memory buffer which, if overflown, overwrites data. To avoid overwriting data, the allocation was reduced.

ODY reduced their UHF return link rate (link from the lander to ODY) to 8 kbps, which resulted in data volume being reduced to 1/16 as compared to the nominal 128 kbps data rate. This was necessary so that MSL could keep overflights long enough to achieve telecommunications lock while keeping the data volumes low as to not overwrite the memory buffer. A five minute overflight during conjunction would only provide on average 2.4 Mbits of data as opposed to the usual 38.4 Mbits. It was MSL/NSY's responsibility (not ODY's) to ensure that the buffer was not overwritten. This required careful planning.

ODY was the only mission continuously transmitting relay data during conjunction, which was done on a best-efforts basis. The expectation was that the ODY data would be garbled, reaching its worst at the lowest SEM angles. The goal was not to use the ODY data for planning, but to see how coherent the data would be and acquire occasional health and safety checks. Although the MSL downlink analysts were not formally performing full downlink assessment, the ODY data were valuable to engineers on MSL to monitor the health and safety of the spacecraft. Even with greatly reduced data volume, the timely receipt of certain chunks of data confirmed that the rover was healthy throughout conjunction.

MRO

In standard relay, data is deleted onboard an orbiter once its receipt is confirmed on Earth. For conjunction, the MRO Solid State Recorder (SSR) was re-partitioned to provide sufficient space to store relay data throughout conjunction, as well as MRO science and engineering data. Approximately 14 Gbit of buffer space was allocated to relay, which MSL and NSY split evenly. MRO stored all the relay data onboard their spacecraft and transmitted that data on September 9, with SEM ~ 2.5 degrees. As with ODY, MSL and NSY were responsible for planning their MRO overflights as to not overflow the relay partition. After conjunction, the SSR was reconfigured to return to pre-conjunction allocations.

Some timing information such as when the orbiters would reconfigure the relay buffer and when they would retransmit the data post-conjunction was not finalized until shortly before conjunction. This was because the orbiters needed to finalize their DSN coverage and build their sequences. MSL had to adapt plans accordingly.

TGO

This was TGO's first solar conjunction so they took a conservative approach to ensure their spacecraft's safety throughout conjunction. As such, they asked the lander teams to gradually reduce the return link data volume for the three weeks before conjunction so that all relay data could be transmitted before conjunction entry. For two of these three weeks, they asked the landers to limit the size of their overflights to 690 Mb/day on average – about a 20% reduction from normal. Then for the last week before entering conjunction, TGO required a further reduction to approximately 128 Mb/day on average – about an 80% reduction from nominal. During conjunction, TGO turned their Electra radio off and entered a 3-week blackout period during which they stopped supporting relay. The data volume constraints were to be repeated in reverse coming out of conjunction, gradually increasing the data volume from 20% in the first week to 80% the following two weeks. However, based on data assessment going into conjunction, TGO cancelled the data volume constraints during the last two weeks and resumed nominal relay support early.

MVN

MVN did not support relay activities during conjunction. The last MVN MSL overflight took place on August 24, with

SEM ~3 degrees. The first MVN post-conjunction trajectory input file, which was needed to resume planning, was not available in time to include MVN in the first post-conjunction strategic planning cycle, so it wasn't until one cycle later that MVN relay planning resumed. This put a limitation on the overall available data volume post-conjunction, in particular during the first week when TGO had data volume restriction.

For all the orbiters that had data volume restrictions (namely, MRO, ODY and TGO), MSL and NSY had the responsibility of ensuring that their collective overflights did not exceed the buffer allocation so that data were not overwritten before they were transmitted to the ground. The two landers discussed their data volume needs pre-, during, and post-conjunction and coordinated usage. Because NSY is solar powered, they requested to use the MRO and ODY PM passes to minimize the energy impact to their lander. A PM pass is an overflight occurring between 1200 and 2359 Local Mean Solar Time (LMST). MSL then took the AM passes, which – though at the time it was not certain this would be the case – worked well because the passes did not conflict with any science activities.

DSN

The final piece of the puzzle was coordinating DSN coverage. DSN scheduling defines the times that operators on Earth are able to communicate (transmit and receive) with spacecraft on Mars. Plans are uplinked via the DSN and MSL returns short signals called *beeps* to inform operators of the vehicle's functional status. Scheduling transmitter time and downlink coverage on the DSN is a process that takes place well in advance of most UHF planning, typically over the span of months. MSL's process involves a member of the Comm planning team interfacing with a DSN scheduler who negotiates with other missions for time using the shared resource that is the DSN.

For this conjunction, MSL followed closely on the experience of previous conjunctions. The result was that MSL would have no DSN coverage at SEM = 2.5 inbound to 2.0 outbound, which equated to 12 days starting on August 27 and ending on September 8. From September 8-11, MSL requested sufficiently long DSN coverage to ensure that engineers at JPL could hear the rovers beeps.

The only complication with DSN scheduling for conjunction was that the DSN has occasional downtimes scheduled many months in advance. Part of MSL's conjunction assessment was to address any downtimes that occurred surrounding critical conjunction dates. This year, there was a DSN maintenance downtime scheduled for August 13th, which was too close to critical deadlines for MSL. MSL requested that this downtime be moved in case any last minute emergencies required the use of the DSN at this time. The DSN complied with this request and moved the downtime to a less critical period.

4. TOOLS

In 2019, the Comm planning team began using a newly developed set of tools to assist with overflight selection. The selection algorithm considers factors including potential data volume return, timing, and crosstalk conflicts. With a growing number of relay assets, selection optimization has become increasingly difficult, so tools are required to assist in the process. This conjunction would be the first time they were used for a conjunction period.

The tools are designed to work with the regularly scheduled file deliveries from each orbiter team. In nominal operations, the due dates for all input and output files are strict and constant, but during conjunction some of these dates shifted. This, along with the constraints on data volume and non-relay periods, required tool updates.

Adjustments

The modifications to the tools included:

- Removing MVN from the overflight selection algorithm because MVN would not perform relay during conjunction
- Adjusting ODY data rate to 8 kbps to accurately reflect data volume return
- Lowering minimum data volume requirements to allow selection algorithm to select ODY overflights despite relatively poor data return

Because of the unique constraints that MSL and NSY each had, many more manual adjustments were required after filtering all overflights through the selection algorithm. Manual changes included:

- Selecting only AM passes in compliance with MSL/NSY negotiations
- Ensuring 1 ODY and 1 MRO pass were selected on each sol
- Shortening and deselecting TGO passes to ensure data volume limitations were not exceeded
- Adding MRO pass margin to account for orbit uncertainty

In the end, the tools functioned well despite being used outside of their standard use case. Though the overhead that comes with sophisticated tools can at times be cumbersome, here they worked well and demonstrated their robustness.

5. SCIENCE

Details of the science performed during conjunction extends beyond the scope of this study, except where it relates to the capability (or lack thereof) of communicating with the rover. For this reason, a brief background on the science performed is required.

Constraints

The downlink data from ODY during conjunction was not sufficient to provide operators adequate knowledge about key measurements like available power, motor position, attitude, and instrument health. This decisional data is typically downlinked on every overflight and analyzed by MSL's downlink team. During conjunction, MSL sent this information to ODY and MRO for relay, but because ODY was the only orbiter transmitting the data back to Earth, all of the data sent via MRO overflights was unavailable to the downlink team. This painted an incomplete picture of downlink telemetry, and thus was not sufficient to operate the rover nominally.

Furthermore, even if downlink was sufficient, operators would not be unable to uplink commands to address any anomalies that may have required human intervention. As a result, the conjunction plan that operators sent to the rover prior to the start of the conjunction command moratorium consisted of a variety of low-risk science activities that did not require human-in-the-loop.

Several mission constraints restrict activities from executing in the interest of rover and instrument health. One such constraint is to leave cameras pointed below a certain elevation when not in use to avoid accumulating dust on the cameras' optics. In normal operations, it is possible that a sequence could execute to point a camera upwards and have the following sequence to "stow" the camera fail. This would leave the camera in an unwanted state. During conjunction, operators cannot uplink a command to reattempt the stow. Thus, the rover would linger in an unwanted state until the end of conjunction, permanently impacting the performance of the camera, and so operators are restricted from ever pointing the camera above level horizon. For many reasons along a similar vein, science activities are heavily constrained.

Many other activities are precluded during conjunction as well, including driving and moving the robotic arm, which houses several instruments and tools on its end– including a closeup imager, spectrometer, rock brush, and sampling drill. Using any of these requires precise positional knowledge; accidentally applying too high of a load to an instrument on the arm, for example, by touching a surface with imprecise position knowledge could cause damage to the instrument or arm motor. Many of the arm's movements must be precise to the millimeter. In nominal operations, the rover captures stereo images of its surroundings to generate 3D meshes that operators use to simulate interactions with local geology with pinpoint accuracy. Acquiring a significant set of these images in new locations is not possible during conjunction because of data volume constraints. Moreover, physically moving the rover wheels or arm is very risky, and without the ability to react to any faults, operators avoid kinetic activities and stick to mainly static ones.

Plans

A conjunction uplink team was assembled to build plans independently from the standard uplink process. The science team provided the uplink team with a set of activities that they wanted to perform and the uplink team built the plans accordingly. As mentioned, the Comm relay passes served as the backbone for everything else in the plans to fit around. The result was two separate 7-day plans, which were heavily templated, looking almost identical day-to-day. Though it normally takes a team 7-8 hours to make a plan for a 1-3 sols, the conjunction team was able to create the conjunction plans in a similar amount of time because of prep work done in advance and the repeating nature of the plans.

The plans included several hours of environmental science activities which occurred throughout the day at standard times. Standard engineering housekeeping activities continued throughout conjunction. Lastly, periodic imaging was added to the plan each day at 12:00 LMST (Local Mean Solar Time) to capture change detection throughout the conjunction period. Two UHF overflights – one ODY and one MRO – occurred in the early hours of the morning, typically between 02:00 and 08:00 LMST. In all, the rover's main computer stayed online for approximately 8 hours each day, and turned off for the rest to conserve power, which is a typical level of use for the computer. Conserving power, which is usually one of the main constraints for MSL's planning team, was not a concern with less demanding plans. Lastly, there were no conflicts between science activities and Comm windows.

The data volume that these plans generated were considerably less than nominal operations, since the data products from permitted instruments are significantly smaller than other instruments. As previously mentioned, the total data volume from ODY and MRO was sufficient to downlink these data products. However, it should be noted that when the Comm planning team begins the process of negotiating overflights, they are unaware of the precise data volume requirements from the conjunction plans' science activities.

6. CONCLUSIONS

The 2019 conjunction was a success from the Comm planning and mission perspectives. No major anomalous behavior was observed onboard the rover and all Comm windows executed nominally, returning all expected data. The Comm planning process was improved and heavily documented to make future conjunction planning significantly easier.

Lessons Learned

It was important to establish a preliminary schedule for all teams as early as possible. Conjunction planning spanned several months and was a very busy time for MSL's Comm planning team, but the pace was acceptable and went smoothly considering the complexity of the planning periods. Selecting the right date for the Comm windows delivery was a crucial first step, which allowed MSL to avoid complicated processes and workarounds such as "spoofing" file deliveries.

All of the relative due dates picked for file deliveries were appropriate for this conjunction. Requesting file deliveries significantly earlier would have put undue stress on multiple teams. A similar schedule for future conjunctions will likely work well.

It should be understood that conjunction plans and details continue to evolve in the weeks leading up to conjunction and possibly even during conjunction. Orbiters have internal sequencing timelines and some may not finalize their sequences until shortly before conjunction. In addition, orbiters may update their post-conjunction plans based on what they observe going into or during conjunction. For example, an orbiter's post-conjunction retransmit could shift to accommodate a lander's need. Additionally, an orbiter could modify some of their data volume constraints. Therefore, MSL should maintain the flexibility to accommodate these changes

Documentation from previous conjunctions consisted of mostly final products, missing some of the finer details of the process. Furthermore, because each conjunction is different, previous documentation will not always be sufficient for future use. This year the Comm team greatly expanded on the existing documentation. Since each conjunction is roughly two years apart and employee turnover is a natural force, it is important that as many aspects of conjunction planning are covered.

The Comm planning process can appear elaborate and convoluted to those not directly involved. Thus, it is important to communicate directly and effectively. Graphics such as the one shown in Figure E were found to be very useful by many members of the larger MSL team. Additionally, designating specific intra-team points of contact for conjunction helps streamline communication. MSL established a dedicated conjunction team with representatives from each sub-team of the mission and held weekly meetings to track the status of conjunction-related items.

The intricacy and off-nominal nature of conjunction planning can greatly increase the risk of mistakes. Good communication, clear timelines, and careful checks help mitigate these risks. Implementing the strategies discussed in this paper should assist in achieving a successful conjunction.

Future Considerations

TGO and MVN have indicated that they would be willing to provide relay support during future conjunctions. Should the need for additional overflights arise, they would make valuable additions. Although the data volume requirements for this conjunction did not necessitate supplemental involvement, it is possible that MSL could make a request to, for example, utilize the conjunction period to downlink large stores of onboard data.

A small, dedicated team of developers is continuously improving the Comm planning tools. Future efforts hope to improve visualization of the overflight trade space and make manual changes easier to implement. In addition, improved input/output tracking will help the Comm team ensure that the proper files are being used and delivered throughout the process – something that is especially pertinent during conjunction.

The arrival of the next Mars rover, NASA's Mars 2020 (M2020), will bring even more complexity to the Comm planning community and will force MSL and NSY to share valuable data volume during conjunction. The current method of negotiations will likely still be capable to plan future conjunctions, though other options could be explored. Both M2020 and NSY may implement a variant of MSL's Comm tools in the near future, which could help streamline the negotiations process.

The introduction of more autonomous features on future spacecraft such as M2020 may lead to an increase in science yield during conjunction by reducing the need for human-in-the-loop. Higher science yield will also demand greater data volume requirements from orbiters. In the distant future, if many more spacecraft inhabit the Mars environment, it seems evident that the needs for conjunction planning will continually evolve.

A preliminary analysis of the ODY downlink during conjunction showed the successful downlink of a limited set of data throughout the entire conjunction period, even at SEM closest to zero. Plot A in *Background* illustrates that some conjunction periods are significantly more disruptive than others. Though some efforts have been made in the past, it may be possible to further investigate the integrity of signals sent from Earth to Mars during conjunction. If additional means of risk mitigation are developed, it may be possible to reevaluate the risk posture for the conjunction command moratorium, potentially shortening the effective conjunction period and resulting in an increase of science yield.

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ACKNOWLEDGEMENTS

The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

The authors would like to thank the following colleagues for their contributions: Andrew Mishkin, Christopher Leeds, Ryan Mukai, Pegah Pashai, Nancy Vandermey, and Ning Liu.

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